DRAFT MEMORANDUM CH2MHILL

Rocky Flats Literature Review - Plant Uptake of Uranium

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Executive Summary

The characteristics of plant uptake and translocation of uranium are highly specific to the type of plant and soil. No information was found on cottonwood or poplar uptake of uranium, and very little information was found on uptake of uranium from shallow groundwater sources.

The most likely forms of plant-available uranium in the shallow groundwater are soluble carbonate complexes, with uranium in a VI+ oxidation state. Plants cannot distinguish isotopes of heavy elements, and therefore take up isotopes in the proportions that they occur in soil solution. The isotopic composition of plant tissue uranium should then mimic the shallow groundwater source.

The concentration ratio is the ratio of plant uranium mass concentration to the total soil concentration. It is the parameter used in ecological risk assessments, although it is a less than ideal tool. Values typically vary over several orders of magnitude. For trees, data collected from a number of sources suggest concentration ratios from 0.001 to 0.02.

Study results vary greatly with regard to uranium uptake by plant species. Some studies have shown little difference in uptake among species. Others, however, have shown that leafy vegetables reach higher concentrations than grain and fruit crops. Generally, the highest concentrations are found in root tissue, where positively charged uranyl ions adsorb to root cell walls. Storage organs tend to have lower concentrations of uranium. No reports have been found specifically describing uranium uptake by *Populus spp*. In a number of studies, only negligible amounts are translocated to the above-ground portion of the plants, generally less than 5 µg/g of plant dry matter. However, one study found that black spruce trees have been found to hyperaccumulate (accumulate in concentrations greatly exceeding those of the soil) uranium in small branches (twigs), with concentrations in twig ash reaching 1300 µg/g (48 µg/g plant dry matter), with lesser concentrations found in leaves and roots.

Soil factors influencing uptake include the amount and species of other cations present, the type of clay minerals, and the pH. Plant uptake of other radionuclides appears to compete with calcium uptake, therefore uranium uptake may tend to be reduced in high-calcium soils. Conversely, high levels of soil phosphorus tend to decrease uptake.

Detailed recommendations for a laboratory study of uranium uptake at this site are provided in a separate document. Key aspects of the study include simulation of site conditions in the study, including plant species, soils from the site, water supply from the lower portion of the root zone, and simulation of groundwater chemistry with special attention to pH, calcium, carbonate alkalinity, and soluble phosphorus. Other recommendations relate to careful removal of surficial dusts from plant tissues before analysis, and sampling by plant part and age.

Purpose

The purpose of this review is to determine what is known about the uptake of uranium (U) in vegetation. The results will help (1) determine whether a laboratory study should be recommended, and (2) guide development of the necessary components of a laboratory study, if it is recommended, to determine site-specific uranium uptake during phytoremediation.

Site Conditions

Shallow groundwater samples in the SPP area indicate nitrate-nitrogen concentrations ranging from less than 5 mg/L to greater than 1000 mg/L, and total U activities ranging from less than 1 picocurie per liter (pCi/L) to greater than 100 pCi/L. Water collected by the ITS has averaged 430 mg/L nitrate-nitrogen and 130 pCi/L uranium.

Uranium Chemistry

Although there are 14 isotopes of U that occur in nature, 99.27 percent of it is found as ^{238}U in naturally occurring (not enriched or depleted) uranium (Schulz, 1965). Uranium is most often found with a valence of VI+ (Bondietti and Sweeton, 1977). It is one of 14 radionuclides with some degree of mobility in soil water, and consequently has potential for plant uptake (Schulz, 1965).

Langmuir (1978) summarized uranium chemistry in natural groundwaters as follows:

> At typical concentrations of chloride, fluoride, phosphate and sulfate, uranous (U^{4+}) fluoride complexes are important in anoxic waters below pH 3 to 4. At intermediate Ehs (between about +0.2 and -0.1 V) and pH values 1-7, UO_2^+ may predominate. In oxidized waters, uranyl (UO_2^{2+}) fluoride complexes and the uranyl ion predominate below pH 5; from about pH 4 to 7.5, $UO_2(HPO_4)_2^{2-}$ is the principle species; while at higher pHs, $UO_2CO_3^0$ and the di- and tri-carbonate complexes predominate.

Therefore, assuming that neutral to alkaline and oxidizing conditions prevail in shallow groundwater at SPP, soluble uranium (available for plant uptake) would be expected to be predominantly complexed with carbonate and possibly phosphate. Recently collected soils data from the site confirm that conditions are alkaline with the soil pH generally around 8. In oxidizing environments, the uranyl (VI+) ion and its complexed forms are mobile (Domenico and Schwartz, (1990) and are therefore the most likely forms of uranium taken up by plants.

As a cation (uranyl UO_2^{2+}), uranium has the potential to adsorb on soil minerals. The extent and tenacity of adsorption depends on many factors, including the adsorption energy of uranium cations, the amount and species of other cations present, the type of clay minerals, and soil pH (Schulz, 1965). Sorption onto natural materials is greatest from pH 5 to 8.5 (Langmuir, 1978). Retention of uranium tends to be greater in finer textured and organic soils because of their greater cation exchange capacity (Sheppard and Evenden, 1988).

Key Points about Uranium Chemistry

The key points derived from the literature review regarding uranium chemistry are as follows:

- *Soluble uranium is the form that is taken up by plants. At SPP, it will probably be complexed with carbonate.*

- *Laboratory studies should be designed to provide this form of uranium to plants.*

Plant Factors

Uptake Mechanisms

The mechanisms of uranium uptake and translocation are plants are still poorly understood (Dushenkov et al., 1997). However, it has recently been shown that the uncomplexed uranyl ion (UO_2^{2+}) moves to the above ground portion of the plant to a much greater degree than it does when complexed with carbonate (Kochain, 1998). There appears to be considerable variation in plant uptake of soil uranium depending on plant species (Mortvedt, 1994). For example, leafy vegetables generally reach higher concentrations than crops that produce fruit and grain (Simon and Ibrahim 1988).

Concentration Ratio

Much of the literature on plant uptake of uranium refers to concentration ratio (CR)s, calculated as shown in the following equation:

$$CR = \frac{\text{Concentration of U in tissue}}{\text{Concentration of U in soil}}$$

Although plant uptake is much more closely related to available uranium than it is to total uranium, many studies of plant uptake of uranium have used total soil uranium concentrations in the denominator, lowering the reported values for CR (Mortvedt, 1994). Even when a uniform methodology is used, CR values may vary over several orders of magnitude, depending on the soil and plant species (Mortvedt, 1994). Comparisons of CR site to site are greatly complicated by the effects of physical, chemical, and biological factors, Ibrahim and Whicker, 1988). It is implied in the CR calculation that there is a linear relationship between total soil uranium concentration and plant tissue concentration (Mortvedt, 1994), but Simon and Ibrahim (1987) showed from their own data and data in the literature that the relationship is clearly non-linear. The situation is described as follows:

> In general, CR values decrease with increases in substrate concentrations over a small range in concentrations. Above this range the CR value asymptotically decreases to a given value that does not change with further increases in soil concentrations (Mortvedt, 1994).

Thus, CR seems to decline to a minimum value as soil U concentrations increase. Sheppard and Evenden (1988) reviewed numerous studies of uranium uptake by plants. The key results of their review of CR values are as follows:

- The overall geometric mean CR for uranium for all plants and all soils was 0.0045. However, CR values often span three to five orders of magnitude for a given element. The CR attempts to expresses the relationship of very complex processes in a very simple way, which leads to very high variability.
- CR values for uranium varied by 30,000-fold for the studies they reviewed. Geometric means and geometric mean standard deviation are the most appropriate ways to summarize central tendency and variability (respectively) of CR data.

- The CR did not relate to soil concentrations in a linear manner; it decreased significantly as soil concentrations increased, primarily because many processes, other than total soil concentration, affect uptake.
- CR values were significantly lower in fine-textured and high organic matter soils.
- The CR is the most commonly used parameter for ecological assessments of food chain transfer risks for elements such as uranium. It has been universally recommended by regulatory agencies, and most environmental assessments continue to rely on it.
- It may be that the correlation between plant concentrations and soil solution concentrations is greater than it is for total soil uranium concentration, but this has not always been found to be the case.
- The increase in plant biomass as plants grow tends to dilute higher rates of uptake associated with increased rates of transpiration.
- Food chain models often express CR in terms of fresh or wet weight of plant tissue. CR values used in mineral prospecting (biogeoprospecting) are often expressed on an ash weight basis. To an extent, the latter method corrects for variables like plant moisture status, plant part, and plant growth stage.
- Extraneous contamination of above-ground plant surfaces can occur under field and lab conditions. This contamination is difficult to measure and to eliminate.
- It is imperative that studies be conducted under very realistic conditions with large volumes of soil and appropriately aged contamination.
- Hydroponic studies cannot be related to uptake under field conditions and cannot be used for the CR. This is because the soil medium largely determines the concentration of soluble U that the plant root is exposed to.
- Pot culture and controlled environment studies may also be unrealistic measures of uptake. To obtain valid data from pot-culture studies, large outdoor containers with natural soil, temperature, and moisture conditions are required. Small-scale studies tend to have very different results from field studies. Overlapping rhizosphere effects may be an important factor resulting in greater uptake in small pots than in the field, because rhizosphere effects can affect uptake by increasing the solubility of radionuclides.
- Radiological assessments will continue to rely on the CR, despite its limitations.

Table 1 shows CR values from many sources compiled by Sheppard and Evenden (1988). Values were adjusted to soil concentrations of 5 μg/g to adjust for the dependence of CR on soil concentration.

Other studies at uranium mining and milling sites have found ^{238}U CR values ranging from 0.0055 to 0.1. One study, however, found a value of 3.3 for unwashed vegetation (Ibrahim and Whicker, 1988). Sheppard et al. (1989) applied 100 mg/kg of uranium to several soils and found an overall geometric mean CR of 0.013 for grain and vegetable crops.

TABLE 1
Weighted Average CR Values for Uranium Adjusted for the Mean Substrate Concentration of 5 µg/g Uranium
Source: Sheppard and Evenden (1988)

	Substrate Material				
Plant Type	**Fine**	**Coarse**	**Organic**	**U-mine Tailing**	**Not Specified**
Native Species					
Trees	0.0022	0.024	0.022	-	0.00097
Shrubs	-	0.0095	0.022	-	0.0009
Annuals	0.0076	-	-	0.0064	0.0016
Cultivated Species					
Cereals	0.0014	0.03	-	-	0.00053
Fruits	0.0025	-	-	-	0.0048
Vegetables	0.0082	0.00050	-	-	0.0019
Root Crops	0.0025	0.02	-	1.9	0.00023
Forage	0.0084	0.00053	-	0.0048	0.0021
Maximum CR	0.0084	0.03	0.022	1.9	0.0021
Minimum CR	0.0022	0.00053	0.022	0.0048	0.00023

Several studies used activity (emission of α-particles) rather than concentration to describe plant uptake and determine CR values. Ibrahim and Whicker (1988) used activity, and calculated the CR based on the ratio of means estimator, based on Gilbert and Simpson's (1983) findings that this estimator works acceptably for data that have normal and log-normal distribution. The ratio of means is simply the mean activity per gram found in dry vegetation divided by the mean activity per gram of dry underlying soil.

Wadey et al. (1994) defined a similar parameter based on activity rather than mass. The parameter, which was called the soil-to-plant transfer function (TF), was defined as the ratio of plant tissue activity to the activity of the soil the plant was grown in, expressed as (pCi/g)/(pCi/g). The IUR (1989) specifies that this is based on plant dry matter and oven-dry soil, and further assumes that all radioactivity resides 0 to 10 cm below ground surface (bgs) for grass and 0 to 20 cm bgs for other species. To address this limitation, Wadey et al. weighted their information by comparing the abundance of roots and specific activity by layer. Uranium was not among the radionuclides studied.

Effect of Isotopic Distribution on Plant Uptake

Plant uptake of uranium is not affected by its isotopic distribution (Dushenkov et al., 1997; Sheppard and Evenden, 1988), and therefore the distribution of uranium isotopes in plant tissue should mimic the distribution of the source of uranium. In the case of this site, isotopic concentration distribution in plants should mimic shallow groundwater concentrations, or those measured at the SPP.

Case Studies

Sheppard et al. (1984) studied uranium uptake and transport from field lysimeters by Swiss chard and alfalfa. They placed uranium-enriched soil at two different depths relative to a shallow water table. Uranium was added to the soil in the form of uranyl nitrate ($UO_2(NO_3)_2 \bullet 6H_2O$) to achieve 0, 50, or 100 μg U/g in a 2 cm horizontal band. There was no difference in uranium uptake between the plants. Concentrations in the above ground plant tissue were found from 0 to 27.6 μg U/g. The placement depth of uranium strongly affected plant uptake in a sandy soil, but did not affect plant uptake in a loamy soil. Uranium migration from the enriched band was significant only in the sandy soil, showing that soil texture strongly affects mobility of uranium.

Sheppard et al. (1985) investigated uranium uptake and translocation in Scots Pine grown in a waste site soil. They used uranium concentrations ranging from 3 to 43 μg/g dry soil. Uranium was primarily concentrated in the roots as compared to shoots, by about two orders of magnitude. In addition, root concentrations exceeded soil concentrations. Shoot uranium concentrations averaged 0.5 to 1.0 μg/g of dry plant, and root concentrations ranged from 57.2 to 148.5 μg/g of dry plant. The relationship between plant concentration and soil concentration was approximately linear for both the shoot and the root; the slopes of the relationships, however, were very different. The CR for seedling shoots was 0.03.

Ibrahim and Whicker (1988) studied uranium uptake by native plants (mixed grasses, mixed forbs, and big sagebrush) at a uranium mining and milling site in Wyoming. Tailings were very acidic. They used ultrasonic washings to attempt to remove surficial dust and associated radioactivity from plant tissues before analysis. They determined that the removal efficiency of this procedure was only 74 percent, indicating that surface contamination may be difficult to remove from plant tissue. They found no major differences in radionuclide uptake in the above ground portion among plant species groups. They used the ratio of $^{238}U/^{234}U$ to determine that both plants and soils were at radioactive equilibrium. The relative in soil and plant uranium concentrations are shown in Table 2.

The data in Table 2 show that plant uptake and translocation of uranium can be significant under certain conditions, and that the CR increased dramatically at high levels of soil uranium.

Van Netten and Morley (1982b) investigated uranium uptake by barley in uranium rich, somewhat alkaline (pH 7.37 to 7.70) soils in British Columbia. Plants were grown for 40 days. With soil concentrations from 3 to 313 μg/g, they found plant concentrations from 1.3 to 15.5 μg/g, and CRs from 0.02 to 0.433. They found that plant concentrations generally increased linearly with soil concentrations.

TABLE 2
Uranium Concentration (mBq/g) in Plants and Soils at a Wyoming Uranium Mining and Milling Site
Source: Ibrahim and Whicker, 1988

	^{238}U		
Location	Soil	Plants	CR
Natural Background	50 (9)	4.4 (0.7)	0.09
Reclamation Area	142 (23)	5.6 (1.5)	0.04
Edge of Tailings Impoundment	407 (322)	130 (48)	0.32
Bare Tailings	503 (63)	407 (85)	0.81

Note: Plant data are the averages for sagebrush, grasses, and forbs tested. Standard deviation given in parenthesis. The plant concentrations shown are from the above ground portions of the plants.

Dushenkov et al. (1997) reported results for the root system of hydroponically grown sunflower to adsorb uranium. The sunflowers successfully removed uranium from groundwater passed through the system. Greater than 1 percent of the root biomass was uranium, and shoot concentrations were less than 5 µg/g. They found that sunflower removed uranium from water more effectively than Indian mustard or beans, indicating the extent of adsorption to plant root tissue varies with species.

Life Cycle Uranium Uptake

Dunn (1986) found that black spruce twigs that were 2 to 5 years old contained the greatest amount of uranium. Older growth contained progressively less (Dunn, 1981). Sheppard and Evenden (1988) suggested that Dunn's results indicated that a redistribution of uranium occurred as trees aged.

Phytotoxicity of Uranium

There is not a great deal of information on uranium phytotoxicity. Meyer and McLendon (1997) found that depleted uranium was not phytotoxic to three species of grass until soil concentrations reached 25,000 µg/g. They used $UO_2(OH)_2 \bullet nH_2O$ (schoepite), a weathered material from deployed munitions, to amend sand in growing chambers. No uranium toxicity was observed in Swiss chard and alfalfa at 100 µg/g soil uranium (Sheppard et al., 1984). Similar results were found for Scots pine by Sheppard et al. (1985)

Translocation of Uranium in Plants

Dunn (1986), investigating uranium uptake and translocation in several varieties of trees, found that twigs (small branches) of black spruce trees were highly effective concentrators of natural uranium in boreal forests as compared to other tree species. In these trees, the concentrations decreased in the order twigs > leaves > roots > trunk. Concentrations of uranium in the black spruce twig ash were found up to 1360 µg/g (approximately 48 µg/g on a plant dry matter basis). The ash of all black spruce twigs analyzed in a 10,000 km^2 area had 10 µg/g uranium.

Dushenkov et al. (1997) found that nearly all (99 percent) of the uranium removed from a uranium-contaminated groundwater was concentrated in the roots of hydroponically-grown sunflowers. In bench tests, the concentration in shoots was not significantly different from the controls, generally below 2 µg/g dry weight. Shoot concentrations reached 5 µg/g only at the highest level of uranium tested, 2430 µg/L. In a subsequent pilot scale test at the U.S. Department of Energy (DOE) Ashtabula, Ohio, site, using an average of 207 µg/L uranium, shoot concentrations were also below 5 µg/g. These tests showed that the rhizofiltration system successfully reduced groundwater concentrations in the flow through the system to below 20 µg/L (the treatment standard). Pilot-scale studies were conducted at pH 5.5. At this pH, chemical modeling showed that most uranium (83 percent) was present as UO_2OH^+ and UO_2^{2+}. They proposed that uranium translocation did not occur because of precipitation or adsorption at the root surface and compartmentalization in root cells. They suggested that uranium cations may bind with negatively charged binding sites in plant (root) cell walls.

Van Netten and Morley (1982a) grew oats in a high uranium soil, and found that root uptake and translocation was not affected by pH, and that roots provided an effective barrier to transport of uranium to the above ground portion of the plant. Soil uranium levels varied from 1 to 574 µg/g, root uranium varied from 0.6 to 131 mg/kg, shoot uranium varied from 0.1 to 3 µg/g, and uranium in seeds varied from 0.3 to 1.5 mg/kg.

Adsorption of uranium on to plant cell walls limits uptake and translocation of uranium in plants, which results in generally greater concentrations in plant roots than the above ground portion of plants (Sheppard and Evenden, 1988). As tissues age, uranium may translocate to other tissues (Sheppard and Evenden, 1988).

Uranium Uptake by Cottonwood (*Populus spp.*)

No data on uranium uptake by cottonwood were found. However, data on ^{226}Ra uptake have been reported. Largetooth aspen (*Populus grandidentata*) near a uranium tailing plant were reported to contain 1.43 picocuries per gram (pCi/g) dry weight in the leaves and 2.67 pCi/g in the stems as compared to 0.11 to 0.14 pCi/g in the controls (Eisler, 1994). Similarly, trembling aspen (*Populus tremuloides*) contained 1.13 pCi/g in the leaves and 1.86 pCi/g in the stems, with 0.08 to 0.41 pCi/g in the controls. In these studies more radionuclide was concentrated in the stems than in the leaves. Translocation of uranium in native cottonwood may differ from these results.

Limiting Plant Concentrations

The transfer of uranium through terrestrial food chains has not been well studied because of high variability in field samples and the expense of analyzing low levels in biota (Garten et al., 1981). Data in studies reviewed above indicate that uranium concentrations in shoots have been found up to 48 µg/g of plant dry matter. The limiting concentration from a regulatory standpoint is not easily defined, and will probably require a separate ecological risk assessment based on the size of the planting, proximity and nature of other habitat nearby, and food-chain pathways (Ohlendorf, 1997).

Hanson and Miera (1976) investigated plant uptake of natural and depleted uranium at munitions testing sites. With uranium concentrations at 2400 μg/g in the 0 to 5 cm layer of the soil, and 1600 μg/g in the 5 to 10 cm layer, plant concentrations were 125 to 320 μg/g dry plant tissue. The CR was 0.05 to 0.08. Small mammals at the site had 2 to 210 μg/g uranium in their body tissues. Hanson and Miera believed that one of the most important mechanisms was resuspension of respirable particles.

The estimated maximum safe dietary intake of natural uranium for sheep and cattle is 20 to 30 mg/kg in the feed, and 10 to 20 mg/L in water. Levels as low as 20 mg U/kg body weight/day have produced adverse effects in animal kidney tissue (NAS, 1980). A daily intake of 0.4 g natural uranium will produce transient depression of milk yield in cows, and 0.05 g/day will produce slight malaise in sheep. The oral acute LD_{50} (lethal dose; 50 percent mortality) in rats is 204 mg/kg body weight as uranyl nitrate (Puls, 1988). Rats may consume 400 parts per million (ppm) uranium in their diet apparently without adverse effect (NAS, 1980). It does appear that animals can achieve a level of tolerance to uranium, in that they can continue to ingest levels without further damage (NAS, 1980). Most uranium ingested is excreted in the urine (NAS, 1980). The major site of physiological deposition is the bone (Linsalata, 1994).

Microorganisms including fungi, algae, and bacteria can accumulate relatively high uranium concentrations, apparently without adverse effects (Hyne et al., 1993). Toxic effects of uranium in organisms often occur when concentrations are such that detoxification mechanisms are overloaded, and uranium binds to proteins (such as enzymes), disrupting their mode of action (Hyne et al., 1993).

Key Points about Plant Factors

- *Although a lot of research has been done on uranium uptake by plants, not enough is known to predict uptake by the proposed system.*
- *Plant concentrations are usually much lower than soil concentrations, and uranium adsorbed to roots is usually much greater than that in the above ground part of the plant.*
- *It is important that the laboratory study carefully reproduces the type of plant to be used in the phytoremediation system and the growing conditions at the SPP.*

Soil Factors Affecting Plant Uptake

A number of soil factors may influence plant uptake and translocation of uranium, including phosphorus, pH, soil texture, total concentration of uranium in the soil, depth to water table, and organic matter content.

Soil Phosphorus

High levels of soil phosphorus may tend to decrease uranium uptake (Van Netten and Morley, 1982).

pH

In sunflowers, greater root adsorption was found at pH 5 than at pH 7 (Dushenkov et al., 1997). However, effects of pH on uranium uptake may vary by plant (Mortvedt, 1994).

Extraction of Uranium from a Shallow Water Table

Wadey et al. (1994) found results that suggested enhanced efficiency of uptake of some radionuclides (^{137}Cs, ^{109}Cd, ^{60}Co, ^{22}Na) in the capillary fringe. No mechanism was proposed, and uptake of ^{238}U was not investigated.

Soil Uranium Concentration

Vegetable concentrations of U increased linearly with soil concentrations (Tracy et al., 1983). Dushenkov et al. (1997) found that uranium concentration in sunflower roots also increased linearly with the concentration of uranium in hydroponic solution. Uranium concentration in the shoot was not affected by solution concentration up to 810 µg/L.

Soil Texture and Organic Matter

Uranium mobility is reduced in finer textured soils and those higher in organic matter (Mortvedt, 1994; Sheppard and Evenden, 1988).

Key Points about Soil Factors

- *Not a great deal is known about soil factors that will influence plant uptake of uranium, suggesting the need for site-specific studies.*
- *Soils used in a laboratory study should be those at the SPP.*

Conclusions

- Soil and plant factors are both very important to uptake, but much remains unknown.
  - No specific data on cottonwood uptake of uranium were found.
  - Very little data on plant uptake from shallow aquifers were found.
  - Alkaline pH of soils the site appear to favor adsorption to the roots rather than uptake to the above ground part of the plants.
  - The CR is the principle parameter used in ecological risk models, but is typically based on total soil concentrations rather than the soluble fraction.
  - The isotopic distribution in plant tissue should match that of the shallow groundwater.
  - When soil uranium levels are elevated, the range of above-ground plant tissue concentrations is often <1 to 25 µg/g plant dry matter.
- A laboratory study appears to be needed.
  - Given the wide variance in the data on plant uptake of uranium, a laboratory study is clearly required.
  - The chemistry of irrigation solutions used in the lab study should closely match the chemistry of shallow groundwater at the site. Particular attention should be paid to groundwater carbonate alkalinity, phosphorus concentration, and temperature in the lab studies.

- Since plant uptake varies greatly by plant species, species to be used at the Rocky Flats site must be tested in the laboratory to allow accurate predictions of field performance.
- Plant sampling should be carefully separated by plant part and age, such as young leaves vs. old leaves, young stems vs. old stems.
- Surface contamination of plant tissue is a concern, and needs to be carefully evaluated and controlled in laboratory and field testing.

References

Bondietti, E.A. and F.H. Sweeton. 1977. Transuranic speciation in the environment. p. 449-476. *In* M.G. White and P.B. Dunaway (ed.) Transuranics in natural environments. NVO-178. NTIS, Springfield, VA.

Domenico, P.A. and F.W. Schwartz. 1990. Physical and Chemical Hydrogeology. John Wiley and Sons, NY.

Dunn, C.E. 1986. Application of biogeochemical methods to mineral exploration in the boreal forests of central Canada. P.133-149. *In* D. Carlisle et al. (ed.) Mineral exploration: Biological systems and organic matter. Prentice Hall, Englewood Cliffs, NJ.

Dunn, C.E. 1981. The biogeochemical expression of deeply buried uranium mineralization in Saskatchewan, Canada. J. Geochem. Explore. 15:437-452.

Dushenkov et al. 1997. Removal of uranium from water using terrestrial plants. EST 31:3468-3474.

Garten et al. 1981. Comparative uptake of uranium, thorium, and plutonium by biota inhabiting a contaminated Tennessee floodplain. JEQ 10:207-210.

Gilbert, R.O. and J.C. Simpson. 1983. Comparing Computing Formulas for Estimating Concentration Ratios, TRAN-STAT, Statistics for Environmental Studies, NO. 23, PNL-SA-11299, Battelle Memorial Institute, Pacific Northwest Laboratory, Richland, WA.

Hanson, F.R. and F.R. Miera, Jr. 1976. Long term ecological effects of exposure to uranium. Los Alamos Scientific Lab. Rep. : LA-6269. NTIS, Springfield, VA.

Hyne et al. 1993. Investigation of uranium-induced toxicity in freshwater hydra. *In* Ecotoxicology of Metals in Invertebrates. R. Dallinger et al. (eds) Lewis Publishers.

IUR. 1989. 6th Annual Report of the Working Group on Soil-to-Plant Transfer. International Union of Radioecologists, Grimselpass, Switzerland.

Ibrahim, S.A. and Whicker, F.W. 1988. Comparative uptake of Uranium and Thorium by native plants at a Uranium production sites. Health Physics. 54:412-419.

Langmuir, D. 1978. Uranium solution-mineral equilibria at low temperatures with applications to sedimentary ore deposits. Geochimica et Cosmochimica Acta. 42:547-569.

Linsalata, P. 1994. Uranium and Thorium decay series radionuclides in human and animal food chains - a review. J. Environ. Qual. 23:633-642.

Meyer, M.C. and T. McLendon. 1997. Phytotoxicity of depleted Uranium on three grasses characteristic of different successional stages. J. Environ. Qual. 26:748-752.

Mortvedt, J.J. 1994. Plant and soil relationships of Uranium and Thorium decay series radionuclides - a review. J. Environ. Qual. 23:643-650.

NAS. 1980. Mineral Tolerance of Domestic Animals. National Academy of Sciences, Washington, DC.

Puls, R. 1988. Mineral levels in Animal Health: Diagnostic Data. Sherpa International, Clearbrook, British Columbia.

Schulz, R.K. 1965. Soil chemistry of radionuclides. Health Phys. 11:1317-1324.

Sheppard, S.C. and W.G. Evenden. 1988. Critical compilation and review of plant/soil concentration ratios for uranium, thorium, and lead. J. Environ. Radioact. 8:255-285.

Sheppard et al. 1989. Uptake of natural radionuclides by field and garden crops. Can. J. Soil Sci. 69:751-767.

Sheppard, M.I., D.H. Thibault, and S.C. Sheppard. 1985. Concentrations and concentration ratios of U, As, and Co in Scots Pine grown on a waste-site soil and an experimentally contaminated soil. Water, Air and Soil Pollution. 26:85-94.

Sheppard, M.I., S.C. Sheppard, and D.H. Thibault. 1984. Uptake by plants and migration of uranium and chromium in field lysimeters. J. Environ. Qual. 13:357-361.

Simon, S.L. and S.A. Ibrahim. 1988. Biological uptake of radium by terrestrial plants: A review. Radium in the environment. Int. Atomic Energy Agency, Vienna, Austria.

Simon, S.L. and S.A Ibrahim. 1987. The plant/soil concentration ratio for calcium, radium, lead, and polonium: Evidence for non-linearity with reference to substrate concentration. J. Environ. Radioact. 5:123-142.

Schulz, R.K., J.P. Moberg, and R. Overstreet. 1959. Hilgardia 28:457.

Simon, S.L. and S.A. Ibrahim. 1988. Biological uptake of radium by terrestrial plants: A review. Radium in the environment. Int. Atomic Energy Agency, Vienna, Austria.

Tracy et al. 1983. Transfer of ^{226}Ra, ^{210}Pb, and uranium from soil to garden produce: Assessment of risk. Health Phys. 44:469-477.

Van Netten, C. and D.R. Morley. 1982a. Differential uptake of U, Mo, and Cu by roots, stalks, and seeds of oats grown on uranium-rich soils. Intern. J. Environ. Studies 19:259-262.

Van Netten, C. and D.R. Morley. 1982b. Uptake of uranium and molybdenum from uranium rich soils by barley. Intern. J. Environ. Studies 19:43-45.

Wadey, P., G. Shaw, J.N. Bell, and M.J. Minski. 1994. Radionuclide transport above a near-surface water table: II. Vertical distribution of gamma activities within soil profiles in relation to wheat rooting density and soil-to-plant transfers. J. Environ. Qual. 23:1330-1337.

APPENDIX

Related Decay Products of Uranium 238

^{238}U and its related decay products are shown in Table 1.

TABLE 1
Isotopes of ^{238}U and Decay Series with Half Lives Greater than 1-Day.
Source: Guimond and Windham, 1975 as cited in Mortvedt, 1994

Isotope	Half-life
--------------- ^{238}U ---------------	
^{238}U	4.5×10^9 yr
^{234}Th	24.1 d
^{234}U	2.5×10^5 yr
^{230}Th	8.3×10^4 yr
^{226}Ra	1620 yr
^{222}Rn	3.83 d
^{210}Pb	22 yr
^{210}Bi	5 d
^{210}Po	138 d
^{206}Pb	Stable